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Computer Simulation of Sensing Current Effects on the Magnetic and Magnetoresistance Properties of a Crossed Spin-Valve Head

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Computer simulation of sensing current effects on the magnetic and magnetoresistance properties of a crossed spin-valve head is carried out. The spin-valve head has the following layer structure: Ta (8.0 nm)/NiMn (25 nm)/NiFe (2.5 nm)/Cu (3.0 nm)/NiFe (5.5 nm)/Ta (3.0 nm), and it is 1500 nm long and 600 nm wide. Even with a high pinning field of 300 Oe and a high hard-biased field of 50 Oe, the ideal crossed spin-valve structure, which is essential to the symmetry of the output signal and hence high density recording, is not realized mainly due to large interlayer magnetostatic interactions. This problem is solved by applying a suitable magnitude of sensing currents along the length direction generating magnetic fields in the width direction. The ideal spin-valve head is expected to show good symmetry of the output signal. This has not been shown explicitly in the present simulation, however. The reason for this is possibly related to the simple assumption used in this calculation that each magnetic layer consists of a single domain.

1. Introduction

High sensitivity and good linear response are very important factors as a read head for the realization of high density recording. Between these two, the linearity of output signals is probably more important than the sensitivity considering recent advances in the field of spin-valve multilayers with high magnetoresistance [1, 2]. Linear response of a spin-valve head is closely related to its magnetic configuration, specifically, the magnetization directions of the pinned and free layers. It is well-known that, although the sensitivity of a spin-valve head is highest when the directions of the two magnetizations and applied field (H_a) are all co-linear, the best linearity is achieved in a so-called crossed spin-valve where the magnetic spin in the pinned layer is directed toward the width direction and that in the free layer toward the length direction. This is the magnetic configuration that is being used in magnetic recording. The direction of H_a (more specifically, the stray field from a recorded bit pattern) in magnetic recording is perpendicular to that of free layer magnetization.

The crossed spin configuration is not "natural" since the spin direction in the pinned layer must overcome the self-demagnetization torque. The realization of this spin structure is assisted by the exchange-biased field (often called the pinning field, H_p) acting on the pinned layer from an adjacent antiferromagnetic pinning layer. Even with this assistance, however, it is not easy to achieve the ideal crossed spin configuration, causing the asymmetry of output signal [3, 4]. This problem becomes more prominent when the size of the sensor element is smaller, since the contribution to the total energy by the magnetostatic interactions increases with the decrease of the sensor size [5, 6].

There are many other parameters, apart from the sensor size, in determining the magnetic configuration. These parameters may include the exchange-biased field, the hard-biased field ($H_{h\text{-}b}$) used to form a single domain structure in the free layer, the uniaxial anisotropy, the exchange field between the two magnetic layers, and the sensing current (i_s). Systematic work is necessary to sort out the role of the parameters, and, as a first attempt, effects of $H_{h\text{-}b}$ were previously investigated by the present authors on the magnetic and magnetoresistance properties of a crossed spin-valve head [7]. Within the model and parameters used previously, the ideal crossed spin-valve structure was not realized, although the ideality was improved by the existence of $H_{h\text{-}b}$. The sensing current, which is known to assist the formation of the crossed spin-valve structure, was not taken into account in the previous work. The aim of the present work is to investigate the effects of the sensing current on the magnetic properties, including magnetoresistance, of a spin-valve head. Work on the sensing current effects in spin-valves was done previously. However, no detailed investigation on the effects of the sensing currents of the magnetic properties of the constituent layers was done, to the best of our knowledge. Effects of high current density on the electromigration, self-fields and thermal heating were examined by Kos *et al.* [8] for a set of spin-valve heads for magnetic

recording. The magnetic configuration of the spin-valve examined by Russek *et al.* [9] was relevant to an MRAM device where the pinning field and the applied field are all parallel to the length direction. Various spin configurations were considered by Portier *et al.* [10] except for the current spin-valve structure, and the sample size considered was rather large being 10 μm × 10 μm.

2. Model and Computation

The model used here was the same as that used previously, so for details, refer to reference [7]. Briefly, each magnetic layer consists of a single domain, indicating that the magnetization is uniform within a layer. Magnetic layers are coupled through the magnetostatic and interlayer exchange interactions. The spin-valve modeled in this work is Ta/NiMn/NiFe/Cu/NiFe/Ta. The modeled spin-valve structure is shown in Fig. 1, together with the definition of the axes. The sensor is 600 nm wide and 1500 nm long. The other parameters including the dimensions, and magnetic and electrical properties are summarized in Table 1. The resistivity values given in the table for the Ta, NiFe and Cu films were taken from the work of Yamada *et al.* [11] who determined the resistivity values by analyzing the variation of the sheet conductance with film thickness based on the Fuchs-Namba model [12].

With no data available in the literature for the NiMn layer, at least to our knowledge, the resistivity of the NiMn layer was assumed to be equal to that of the Ta layer. This assumption is considered to be reasonable, since, in a multilayer spin-valve containing both Ta and NiMn layers, the current densities of the two layers are identical to each other [13]. The antiferromagnetic layer is assumed to be pinned very strongly in the width direction, so its magnetization is essentially fixed. The unidirectional exchange-biased field is 150 or 300 Oe and points in the +y direction. In the pinned and free layers, the uniaxial induced anisotropy with a strength of 5 Oe is assumed to be formed in the x direction. Unidirectional $H_{h\text{-}b}$ is applied to both the pinned and free layers in the +x direction and its magnitude is 25 or 50 Oe. The value of i_S ranges from 0 to 6 mA, and its direction is in the +x direction. The change of the magnetoresistance is calculated by using the expression $\Delta R=1-\cos\theta$, where θ is the angle between the magnetization directions of the two magnetic layers. The magnetic field is applied in the width direction (y axis) and is cycled between +500 and −500 Oe, in order to observe how the magnetic and magnetoresistive properties vary with H_a.

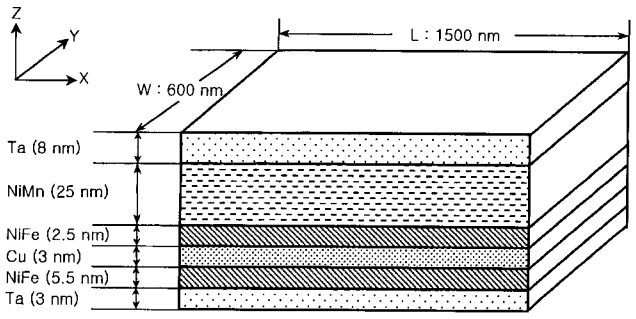

Fig. 1. The spin-valve structure modeled in this work, together with the definition of the axes.

Table 1. The thickness, saturation magnetization and the resistivity of the constituent layers of the spin-valve modeled in this work

Layer Type	Thickness (nm)	Saturation Magnetization (emu/cc)	Resistivity ($\mu\Omega$cm)
Ta (I)	8.0	0	180
NiMn	25.0	0	180
NiFe (pinned)	2.5	800	40
Cu	3.0	0	6.5 or 13.0
NiFe (free)	5.5	800	40
Ta (II)	3.0	0	180

3. Results and Discussion

In Fig. 2 are shown the results for the magnetization directions of the pinned and free layers as a function of i_s before applying magnetic field (at H_a=0) to see the initial magnetization configuration of the spin-valve. The value of $H_{h\text{-}b}$ is fixed at 25 Oe, but two different values of H_p (150 and 300 Oe) are considered to examine its dependence of the initial magnetization configuration. With the present magnetic parameters used here, the magnetization is always confined to the xy plane. This is readily expected from a very large demagnetization factor in the thickness (z) direction. So, the magnetization direction can be specified by an angle in the xy plane and the angle used in this work is defined to be between the magnetization direction and the +x axis. The symbols, θ_p and θ_f, are used to denote the magnetization angles of the pinned and free layers, respectively.

In the case of H_p=150 Oe, the magnetization directions of the pinned and free layers are respectively away from the pinning (+y) and the easy (x) directions at i_s=0, the angles being 98° (the pinned layer) and −22° (the free layer). The canting of the pinned layer, in spite of a rather strong pinning field (150 Oe), is mainly due to the magnetostatic field, particularly the self-demagnetization field which acts to rotate the spin in the length direction. The self-demagnetization field is dependent on the layer geometry, and is related to the shape anisotropy, the magnitude of which is equal to the difference of the self-demagnetization fields in the x and y directions (note that the spins reside in the xy plane only in this work). The values of the shape anisotropy are 27 and 55 Oe, respectively, for the pinned and free layers. In the case of the free layer, the demagnetization field,

together with the uniaxial anisotropy field, tries to align the spin in the length direction. However, the interlayer magnetostatic field (due to the stray field) causes the magnetization away from the easy axis. The free layer deviates more from the ideality than the pinned one, and this can be expected from the strong pinning field acting on the latter layer. Since the magnetization directions of the two magnetic layers deviate substantially from the ideal crossed spin-valve structure, the output signal is expected to be quite asymmetrical in this caes.

As the value of i_s increases, the free layer spin rotates towards the +x direction, but the pinned layer one is further away from the +y direction. This change of θ_p and θ_f can be explained from the direction of the magnetic field generated by i_s (H_i). With the present spin-valve structure and the direction of i_s (+x), the directions of H_i point to the –y and +y directions in the pinned and free layers, respectively. The magnitude of H_i is linearly proportional to i_s and is rather large, being 118.4 Oe/mA for the pinned layer and 85.6 Oe/mA for the free layer. At low i_s values below 0.5 mA, the variation of θ_f with i_s is greater than that of θ_p due to the strong H_p acting on the pinned layer, although a higher value of H_i is generated in the pinned layer than in the free layer. This difference in the i_s dependence of θ_p and θ_f in the low i_s range results in the improvement of the ideal spin structure. In other words, the deviation from the ideality decreases with the increase of i_s. The ideal crossed spin-valve configuration, however, cannot be realized. The changes of θ_p and θ_f with i_s are relatively small at low i_s values below 0.6 mA. In the range of 0.6 to 1.0 mA, however, the magnetization direction varies with i_s significantly, since H_i prevails in this range. Resultantly, the spins in the two magnetic layers are aligned in the H_i directions; namely, the pinned layer spin in the –y direction and the free layer in the +y direction. The large change of the magnetization direction of the free layer in this i_s range can easily be understood, since the value of H_i in this layer is substantially larger (~86 Oe at 1 mA, for example) than the other fields. On the other hand, the spin rotation towards the –y direction in the pinned layer appears hard to understand considering that the value of H_p (150 Oe) is larger than that of H_i (~120 Oe at 1 mA). The spin rotation of the pinned layer, however, is assisted by a large inter-layer magnetostatic field from the free layer which acts to rotate the pinned layer spin to the –y direction.

In the case of H_p=300 Oe, the change of the magnetization direction with i_s is qualitatively similar to that for H_p=150 Oe. One main difference is that, at i_s values below 1.0 mA, the free layer spin rotates slowly to the +x direction, and the pinned layer spin remains nearly constant, pointing in the +y direction, due to the strong pinning field. This variation of the spin direction with i_s results in the realization of nearly ideal crossed spin-valve structure. The most ideal spin configuration is obtained at i_s=0.6 mA where θ_p=98° and θ_f=0°. With the further increase of i_s, large changes in θ_p and θ_f are observed. Again, a steep change of θ_p occurs at a H_i value (180~240 Oe in the i_s range 1.5~2 mA) substantially smaller than H_p (300 Oe). This is due to a large interlayer magnetostatic field acting on the pinned layer from the free layer which tries to rotate the pinned layer spin to the –y direction. It is worth noting a very steep change of θ_p (similar to the λ-like change) at $i_s \cong 2.0$ mA. The peak occurs at i_s=1.897 mA where θ_p=326° (–34°) and θ_f=85°, both spins pointing to the +x direction. At an i_s value just below the peak, say i_s=1.896 mA, θ_p=227° (–133°) and θ_f=67°. These sudden changes of θ_p and θ_f (particularly θ_p) can be explained as follows. In the presence of $H_{b\text{-}h}$, the free layer spin resides in the +x hemisphere and this causes the pinned layer spin to stay in the –x hemisphere, since the interlayer magnetostatic field is larger than $H_{b\text{-}h}$. However, as θ_f approaches 90°, the field component in the –x direction by the interlayer magnetostatic interaction acting on the pinned layer from the free layer becomes small, eventually this field component becoming smaller than $H_{b\text{-}h}$ causing the pinned layer spin to jump from the –x to +x hemisphere.

Although the i_s range investigated in this work is quite wide up to 6 mA, the spin configuration close to the crossed spin valve structure is limited to a small i_s region. This is quite different from the actual situation where the value of i_s is known to be several mA, indicating that the parameters used here are not very realistic. In an effort to rectify this situation, the value of $H_{b\text{-}h}$ is increased from 25 to 50 Oe, and the resistivity of the Cu layer (ρ_{Cu}) is doubled

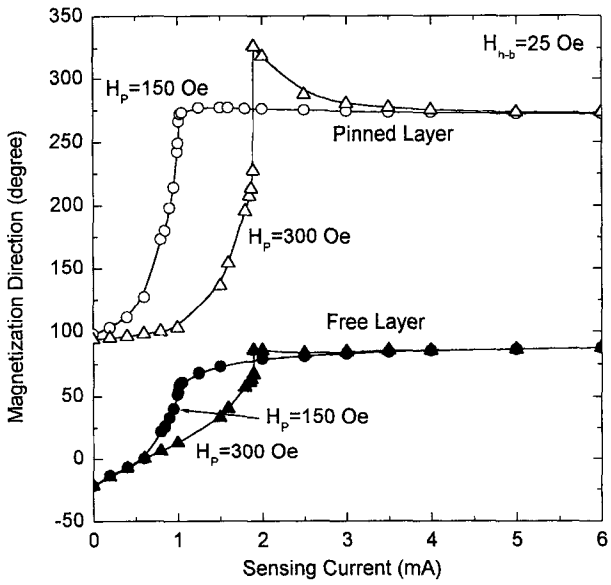

Fig. 2. Initial magnetization directions of the pinned and free layers measured at zero applied field as a function of the sensing current. The value of $H_{h\text{-}b}$ is fixed at 25 Oe, but two different values of H_p (150 and 300 Oe) are considered to examine its dependence of the initial magnetization configuration. The spins reside in the xy plane and the angle is between the magnetization direction and the +x axis.

from 6.5 to 13.0 $\mu\Omega$cm. This increase of the resistivity has an effect of decreasing the H_i by half; specifically, the increment of H_i is 59.2 Oe/mA for the pinned layer and 42.8 Oe/mA for the free layer. In Fig. 3 are shown the results for the magnetization directions of the pinned and free layers as a function of i_s before applying magnetic field (at H_a=0). In order to see the resistivity effect more clearly, the results at the low resistivity are also shown in the figure. The pinned layer spin points to the +y direction due to the strong pinning field. The free layer spin, however, is deviated from the +x direction in spite of the high $H_{b\text{-}h}$ value. This is of course due to the interlayer magnetostatic field acting on the free layer in the –y direction. The pinned layer spin remains nearly unchanged up to i_s =1 mA again due to the strong pinning field, but the free layer spin rotates towards the +x direction with the increase of i_s. As a results of this, the ideal crossed spin-valve structure is achieved; at i_s =0.6~0.8 mA when ρ_{Cu}=6.5 $\mu\Omega$cm, and at i_s =0.8~1.0 mA when ρ_{Cu}=13.0 $\mu\Omega$cm. It is worth noting here that spins in both the pinned and free layers stay in the +x hemisphere due to the high $H_{b\text{-}h}$ value. This is to be compared with the previous case for $H_{b\text{-}h}$=25 Oe where the pinned layer spin usually stays in the –x hemisphere.

Magnetic field is cycled between +500 and –500 Oe in the width direction in order to see the dependence of the magnetic and magnetoresistive properties on H_a. In Fig. 4 are shown the results for the magnetization directions of both the pinned and free layers as a function of H_a during the whole cycle at fixed i_s values of 0, 0.6, 1.25 and 2.0 mA. The other parameters used are; $H_{h\text{-}b}$=50 Oe, H_p=300 Oe, and ρ_{Cu}=6.5 $\mu\Omega$cm. In the case of i_s=0, the magnetizations of both the pinned and free layers point to the directions close to +y at high H_a values, indicating that the Zeeman energy prevails in this region. Even at the highest applied field of 500 Oe, however, both spins do not point to the H_a (+y) direction exactly, the deviation from the +y direction being greater in the free layer than in the pinned layer. As H_a decreases, the magnetization direction rotates further away from the +y direction, principally due to the shape anisotropy. The rotation of the free layer is larger than that of the pinned layer, and this can be understood from the existence of the pinning field in the pinned layer. This rotation of the free layer, in turn, causes to rotate the pinned layer into an angle even close to 90°, through interlayer magnetostatic interactions. As θ_f reaches 0°, a plateau occurs where θ_f does not vary with H_a. This plateau, which occurs in the H_a range 44 Oe $\leq H_a \leq$ 68 Oe, can be explained by the stabilization of the free layer by the self-demagnetization field, the uniaxial field and the hard-biased field. A similar plateau is also observed when θ_p=0° (in this case $\theta_f \cong$ –90°) in the H_a range –428 Oe $\leq H_a \leq$ –416 Oe. The reason for the formation of this plateau is the same for the θ_f=0° case. The H_a dependence of θ_p and θ_f in the presence of i_s is similar to that in the case of i_s=0. One most obvious feature is that, as i_s increases, the spin in the pinned layer begins to rotate to the –y direction at a small Zeeman force component in this direction, but the spin in the free layer rotates at a high Zeeman force. At i_s=2.0, for example, the pinned layer spin deviates significantly from the +y direction even at positive H_a values, causing the pinned layer to switch earlier than the free layer. This H_a dependence of θ_p and θ_f as a function of i_s can be expected from the direction of H_i in each layer (the –y direction in the pinned layer and the +y direction in the free layer). It is of interest to observe a broad maximum in the θ_p-H_a curve at i_s=1.25, and a similar minimum in the θ_p-H_a curve at i_s=2.0. This appears strange being against the Zeeman energy. As the Zeeman force component in the –y direction increases, the spin direction rotates back to the + y direction in the case of the broad maximum in the θ_p-H_a curve at i_s=1.25, and the spin direction is away from the –y direction in the case of the minimum in the θ_p-H_a curve at i_s=2.0. This strange behavior is due to a strong interlayer magnetostatic field. For example, the maximum in the θ_p-H_a curve can be explained by a strong interlayer magnetostatic field acting on the pinned layer in the –x direction from the free layer which points to the +x direction.

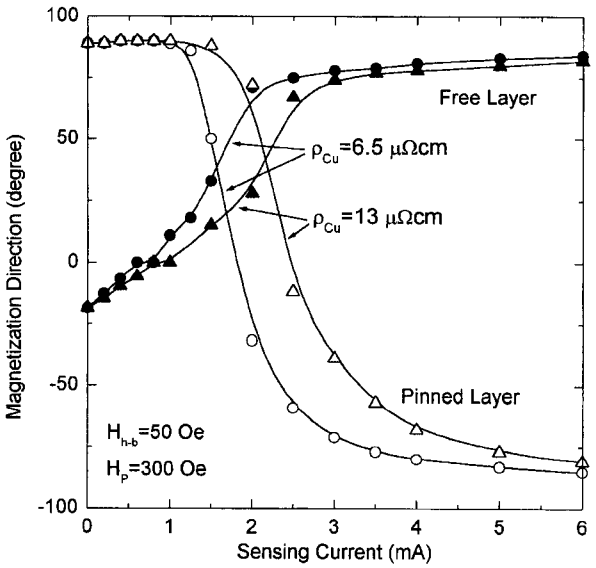

Fig. 3. Initial magnetization directions of the pinned and free layers measured at zero applied field as a function of the sensing current. The values of $H_{h\text{-}b}$ and H_p are fixed at 50 and 300 Oe, respectively, but two different values of Cu resistivity are considered to examine its dependence of the initial magnetization configuration. The spins reside in the xy plane and the angle is between the magnetization direction and the +x axis.

The H_a dependence of magnetization and magnetoresistance can be evaluated from the results shown in Fig. 4 for θ_p and θ_f as a function of H_a, and the results for these properties are shown in Fig. 5 (magnetization) and Fig. 6 (magnetoresistance). The results are shown at fixed i_s values of 0, 0.6, 1.25 and 2.0 mA, and the parameters used are the same with those in Fig. 4. A progressive change occurs for the magnetization curves for i_s=0, 0.6 and 1.25. As H_a

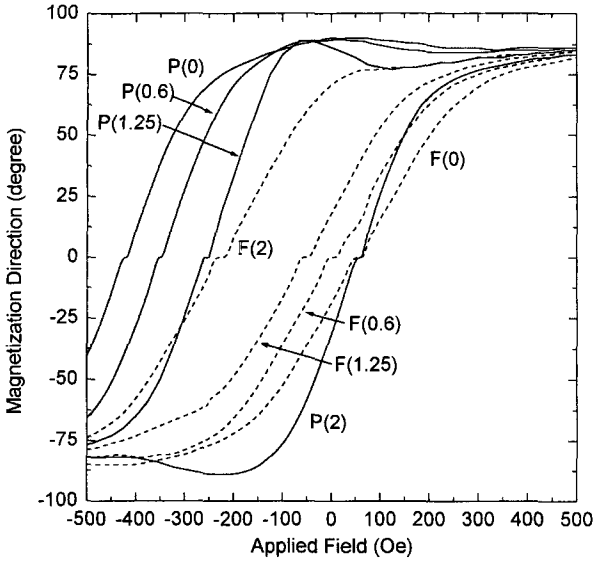

Fig. 4. Magnetization directions of the pinned and free layers during the whole cycle of applied field at various sensing currents of 0, 0.6, 1.25 and 2.0 mA. The spins reside in the xy plane and the angle is between the magnetization direction and the +x axis. The letters P and F, respectively, denote the pinned and free layers.

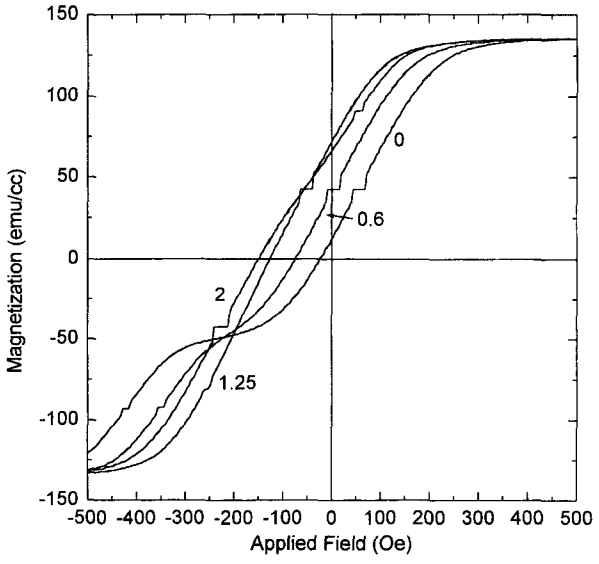

Fig. 5. M-H hysteresis loops at various sensing currents of 0, 0.6, 1.25 and 2.0 mA. The numbers at the curves denote the values of the sensing current.

decreases from the maximum applied field of 500 Oe, the value of H_a at which magnetization begins to decrease is larger at smaller i_s values. This is because the magnetization change in this region is dominated by the free layer, and the magnetization rotation of the free layer is hindered by H_i, whose direction points to the +y direction. The saturation in the negative direction, however, is reached more easily at larger i_s values, since, in this H_a range, the magnetization change is dominated by the pinned layer, and the magnetization rotation of the pinned layer is assisted by H_i, whose

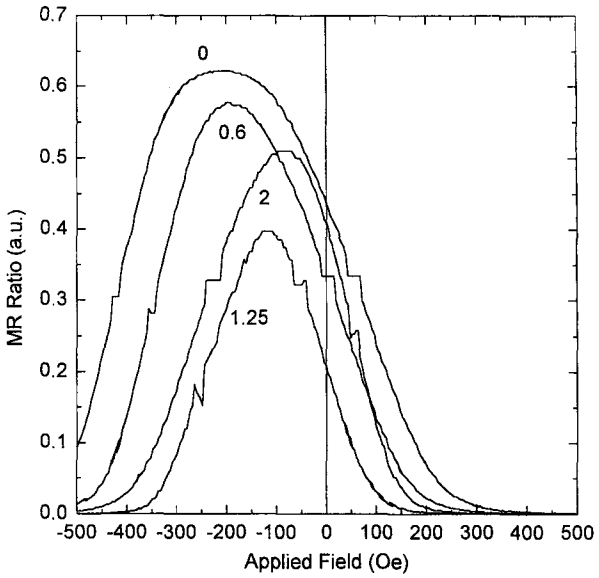

Fig. 6. The giant magnetoresistance curves at various sensing currents of 0, 0.6, 1.25 and 2.0 mA. The numbers at the curves denote the values of the sensing current.

direction points to the −y direction. On the other hand, the magnetization curve at i_s=2.0 is different from the other curves for the lower i_s values, mainly because the pinned layer begins to switch earlier than the free layer. In all the cases, no hysteresis is observed, indicating that the magnetization occurs mainly by a continuous rotation of magnetization, not by a sudden spin flip. This can be expected in a crossed spin-valve structure.

Let us finally consider the magnetoresistance behavior. The magnetoresistance near $H_a \cong 0$ which is practically important is dominated by the rotation of the free layer at i_s =0, 0.6 and 1.25. In the case of i_s=2.0, however, it is dominated by the pinned layer. Considering this spin behavior, it is rather unexpected that the magnetoresistance is also large at this sensing current. This situation is not realistic and will not be considered in the following discussion. For the given H_a cycle, the magnetoresistance ratio is highest at i_s=0, and it decreases with increasing i_s. The best linearity is expected to be observed at i_s=0.6 where the ideal spin-valve structure is achieved. However, it is hard to conclude from the present results, since the plateau exists at $H_a \cong 0$. The existence of the plateau, which is not usually observed in a real crossed spin-valve, may be due to the assumption of the present model that each layer consists of a single domain. Although the single domain assumption is simple and efficient from the calculation point of view, and has been used successfully in many micromagnetic simulations, the present result may indicate that a caution should be exerted to use this simple assumption. If the plateau is not considered and this region is interpolated by considering the results outside the plateau, it seems that the best linearity is obtained at i_s=0.6 where the ideal spin-valve structure is achieved at H_a=0

4. Conclusions

Computer simulation has been carried out in this work to examine the effects of sensing current on the magnetic and magnetoresistance properties of a crossed spin-valve head. Particular emphasis has been placed on the symmetry of the output signal, which is essential to high density recording. The spin-valve head modeled in the calculation is Ta (8.0 nm)/NiMn (25 nm)/NiFe (2.5 nm)/Cu (3.0nm)/NiFe (5.5 nm)/Ta (3.0 nm), with a length of 1500 nm and a width of 600 nm. A simple model has been used in this work, where each magnetic layer consists of a single domain, and the magnetoresistance is calculated by using the expression $\Delta R=1-\cos\theta$, where θ is the angle between the magnetization directions of the two magnetic layers. The patterned head with small dimensions possesses large magnetostatic interactions so that the ideal crossed spin-valve structure is not realized even with a high pinning field of 300 Oe and a high hard-biased field of 50 Oe. This problem is solved with the application of sensing currents along the length direction generating magnetic fields in the width direction. The best signal symmetry is expected at the condition showing the ideal spin-valve structure. However, this has not been demonstrated in the present simulation, since a plateau exists in the practically important region of $H_a \cong 0$. The reason for the existence of the plateau is possibly related to the simple assumption used in this model that each magnetic layer consists of a single domain. The present result may indicate that a caution should be exerted to use the simple assumption of the single domain model.

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